STATE VARIABLE AND PARAMETER ESTIMATORS HAVING A PLURALITY OF SUBMODELS FOR AN ELECTRICAL ENERGY STORE

Field Of The Invention

The present invention relates to the determination of state variables and parameters of a mathematical energy storage model, especially a battery model.

5   ## Background Information

In electrical networks, such as in motor vehicle electrical systems, as a rule, several electrical users are supplied with power by one electrical energy storage device, such as a battery. In order to perform energy management and user management, in which users, depending on requirements, may be automatically switched on and off, knowledge of the capacity of the

10   energy storage device is of essential importance. If the capacity of the energy storage device is known, especially the load that may still be drawn before undershooting a requisite minimum capacity, such as for an engine start, then, even before a short supply sets in, use-reducing or capacity-increasing measures may be introduced, such as switching off certain users, and thus a failure of the electrical supply may be prevented.

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In order to estimate the capacity of the energy storage device, it is known that one may use mathematical models that describe the electrical properties of the energy storage. While taking into account current operating variables of the energy storage, such as a current battery voltage U_{Batt}, the current battery current I_{Batt} and the current battery temperature T_{Batt}, the

20   capacity of the energy storage device may be estimated, with the aid of the mathematical models. A device, known from the related art, for determining the load that may be drawn from an energy storage, is shown in Figure 1.

Summary Of The Invention

25   Figure 1 shows a device for determining the load that may be drawn from an energy store, especially from a vehicle battery, up to a prespecified cutoff criterion. The device includes a state variable and parameter estimator 1, and a load predictor 2, in which the mathematical energy storage model is stored. State variable and parameter estimator 1 is used to calculate state variables Z and/or parameters P from current operating variables of the battery, namely

the battery voltage U_{Batt}, the battery current I_{Batt} and the battery temperature T_{Batt}, based on which load predictor 2 calculates the desired information, such as the load Q_e that may be drawn from the battery, or other variables, such the time t_e to the time of reaching a cutoff criterion or load state SOC. In addition, a discharge current profile $I_{Batt,Entl}$ and a

5   temperature progression $T_{Batt,Entl}$ may be supplied to load predictor 2.

In this description, as state variables Z are counted especially internal voltages U, which are seen in the respective equivalent circuit diagram of the energy storage device or the mathematical model on which it is based. In the case of the named parameters, constant

10 values are involved, such as resistances R and storage capacities C in the equivalent circuit diagram or the mathematical energy storage model.

The load computation carried out by load predictor 2 takes place starting from the current state of the energy storage device. Therefore, the mathematical models stored in load

15 predictor 2 are first initialized to the operating state of the energy storage device. For this, state variable and parameter estimator 1 supplies the corresponding initial values. A known Kalman filter may be used, for instance, as a state variable and parameter estimator. Starting from the initialization state, load predictor 2 may calculate, for example, load Q_e that may be drawn from the energy storage for a predefined discharge current and a current battery

20 temperature.

Figure 2 shows an example of an equivalent circuit diagram for the discharge operation of a lead battery ($I_{Batt} < OA$, $U_{Dp} < OV$, $U_{Dn} < OV$). In this context, the individual equivalent circuit diagram variables are as follows, from left to right:

25 R (U_{CO}, U_e, T_{Batt})   ohmic internal resistance, dependent on open-circuit voltage Uco, electrolyte voltage U_e and acid temperature T_{Batt}

UR_i ohmic voltage drop

C_0 acid capacity U_{CO} open-circuit voltage

R_k (U_{CO}. T_{Batt})   acid diffusion resistance, depending on the open-circuit voltage U_{CO}

30 (degree of discharge) and acid temperature T_{Batt}

tau_k $= R_k * C_k$ (time constant of the acid diffusion) is assumed to be a constant of the order of magnitude of 10 min.

U_k concentration polarization

U_e $= U_{CO} + U_k$ (electrolyte voltage)

U_D (I_{Batt}, T_{Batt}) stationary charge transfer polarization at the positive electrode of the battery (U_{Dp}) and the negatice electrode ($U_{D'}$), dependent on battery current I_{Batt} and the acid temperature T_{Batt}

U_{Batt} terminal voltage of the battery

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The individual equivalent circuit diagram variables refer to various physical effects of the battery, which are known to one skilled in the art from the relevant literature.

For ohmic internal resistance R_i, for example, the following relationship may be applied:

$$R_i (U_{CO}, \quad U_e, T_{Batt}) = R_{i0} (T_{Batt}) * (1 + R_{I,fakt} * (U_{COmax} - U_{CO})/(U_e \quad - U_{e,grenz})),$$

10    $R_{iO} (T_{Batt}) \quad = R_{i025} / (1 + TK_{Lfakt}) * (T_{Batt} - 25^0 C)$

where

R_{i025} ohmic internal resistance at full load and $T_{Batt} = \quad 25^0 C$

TK_{Lfakt} temperature coefficient of the battery conductivity

R_{Ifakt} characteristics map parameter

15   U_{COmax} maximum open-circuit voltage of the fully loaded   battery

$U_{e,grenz}$ electrolyte voltage at cutoff (varies with aging)

For other equivalent circuit diagram variables (e.g. U_D, U_k), load predictor 2 includes other correspondingly suitable mathematical formulations. The mathematical model of the energy

20   storage device includes mathematical formulations, at least for the internal resistance R_i, acid diffusion resistance R_k and a charge transfer polarization U_D.

The state variables supply the information about the energy content of the energy storage device of a system. In the equivalent circuit diagram they correspond to the voltages at the

25   storage capacitors, that is, U_{CO} and U_k. For the model-based determination of the capacity of the energy storage device, besides the state variables, the model parameters also have to be known. In particular, parameters that are greatly subject to changes due to aging, such as parameters R_{i025} and $U_{e,grenz}$ have to be adapted to the characteristics curve of the ohmic resistance.

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State variables Z and parameters P that are ascertained by state variable and parameter estimator 1 may be used, for example, for the determination of the load state of the battery, a current or future capacity, as well as, for example, the load that may be drawn from the energy storage device.

Customary predictors (estimating devices), such as, for instance, load predictor 2 shown in Figure 1, usually include very costly models having many state variables and parameters which cover the behavior of the energy storage device over a wide working range. The

5   computation of the state variables and the parameters is correspondingly costly and complicated. On the other hand, other predictors include simple models having few state variables and parameters, which, however, describe the behavior of the energy storage device only at certain working points or at certain frequencies.

10   Therefore, it is the object of the present invention to create a simple and rapid method for estimating state variables and/or parameters for a mathematical energy storage model, which has validity over the entire working range and frequency range of the energy storage device.

The essential idea of the present invention is to provide, in the state variable and parameter

15   estimator, a plurality of mathematical submodels for estimating state variables and/or parameters, which apply at different working ranges and/or frequency ranges of the energy storage device. In this context, the working ranges and/or the frequency ranges of the individual submodels may overlap. Overall, the submodels essentially cover the entire frequency range and working range of the energy storage device.

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This makes it possible to have a continuous estimating of state variables and parameters in the entire working range and frequency range of the energy storage device. By utilizing the submodels according to the present invention, the number of state variables and parameters, that are to be estimated, may be kept small, and thereby the danger of an ambiguous estimate

25   may be minimized. Furthermore, by the subdivision into submodels, a more effective utilization of processor capacity is made possible: "Slow" submodels having large time constants are able to be processed independently of "rapid" submodels having a smaller scanning rate.

30   Preferably, a current (I_{Batt}) or a voltage (U_{Batt}) of the energy storage unit is supplied to the submodels, the current (I_{Batt}) or the voltage (U_{Batt}) being restricted by a filter to the frequency range that is valid for the respective submodel. Thus, highpass filters, lowpass filters or bandpass filters may be preconnected to the submodels.

According to one preferred specific embodiment of the present invention, an error is ascertained between an operating variable (U_{Batt}, I_{Batt}) of the energy storage device and an operating variable (U_{Batt}, I_{Batt}) calculated by a submodel, and is coupled back into the respective submodel (self-feedback). Because of the self-feedback, the state variables and

5   parameters that are to be calculated may be adapted to the actual state of the energy storage device.

Optionally, the error may also be coupled back into another submodel (external feedback). Because of the external feedback, the state variables and parameters, which are being

10   simultaneously calculated by several submodels, may be adjusted with respect to one another.

The errors that are supplied to a submodel by self-feedback or external feedback are preferably weighted using a weighting factor. In this way the sensitivity of a submodel may be set with respect to different errors.

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State variables and/or parameters which were estimated by a submodel and are also included in another submodel are preferably also supplied to the other submodel. There they may be used as starting values, fixed values or as correcting values for the estimation.

20   According to one preferred specific embodiment of the present invention, a stimulation device is provided, using which, an operating variable (current or voltage) supplied to the submodels may be brought into a working range or a frequency range that applies to the submodel.

25   Brief Description Of The Drawings
Figure 1 shows a device known from the related art for calculating the load that is able to be drawn from an energy storage device.

Figure 2a shows an equivalent circuit diagram for a lead battery during a discharge procedure

30   at low frequencies.

Figure 2b shows an equivalent circuit diagram for a lead battery at high frequencies.

Figure 3a shows the construction of a state variable and parameter estimator having a plurality of submodels according to a first specific embodiment of the present invention.

Figure 3b shows the construction of a state variable and parameter estimator having a plurality of submodels according to a second specific embodiment of the present invention.

Figure 4 shows a flow chart for showing the function of a stimulator.

Figure 5 shows the construction of a state variable and parameter estimator for calculating the internal resistances of a battery.

Detailed Description

Reference is made to the introductory part of the specification regarding the clarification of Figures 1 and 2a.

Figure 3a shows the design principle of a state variable and parameter estimator 1 according to a first specific embodiment of the present invention. As may be seen, state variable and parameter estimator 1 includes a plurality of submodels 4, 5 which are in each case effective only in a certain frequency range and/or working range (f1,A1 or f2,A2), and which may thereby be kept very simple. However, submodels 4, 5 in their entirety cover the whole frequency range and working range of energy storage device 3.

Frequency ranges f1,f2,... and working ranges A1,A2,... may partially overlap. In the most favorable case, the entirety of submodels 4, 5 should at least, however, cover a working range A and a frequency range f of the energy storage unit that is as big as possible.

The working range of a submodel 4, 5 is specified by predefined conditions for battery current I_{Batt}, battery voltage U_{Batt}, battery temperature T_{Batt}, state variables Z and battery parameters P.

Individual state variables Z and parameters P may simultaneously appear and be estimated in several submodels 4, 5.

State variable and parameter estimator 1 shown in Figure 1 includes at its input continuously measured battery values, in the present case, battery current I_{Batt} (optionally, battery voltage U_{Batt} may also be supplied) and battery temperature T_{Batt}. Battery current I_{Batt} is restricted by suitable lowpass, highpass or bandpass filters 6, 7, 8, 9 respectively to frequency range f1, f2,

5   in which the respective submodel 4, 5 is valid. A submodel 4, 5 (e.g. submodel 4), which is valid, for instance, in a frequency range f1 of more than 1 kHz, has, in the present case, a preconnected highpass filter 6. For example, a lowpass filter 7, 9 may be preconnected to submodel 5. If a submodel 4, 5 covers the entire frequency range f, input filters 6, 9 for current and voltage may be omitted.

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From the variables supplied, submodels 4, 5 respectively calculate a battery state variable ($I_{Batt}\wedge$ or $U_{Batt}\wedge$). The corresponding actual value (I_{Batt} or U_{Batt}) is supplied to state variable and parameter estimator 1 as a measured value from outside. Estimated values $U_{Batt,1}\wedge$, $U_{Batt,2}\wedge$ or quantities derived therefrom (error signals) are fed back into the respective submodel 4, 5.

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State variable and parameter estimator 1 includes difference nodes 17, 18 at which an error (differential signal) is formed from the estimated battery state variable $U_{Batt,1}\wedge$, $U_{Batt,2}\wedge$ and the respectively measured battery state variable $U_{Batt,1}$, $U_{Batt,2}$. The ascertained errors ($U_{Batt,1}$ - $U_{Batt,1}\wedge$, $U_{Batt,2}$ - $U_{Batt,2}\wedge$, ...) are then in each case supplied to a weighting unit 1.0, 12 and

20   conducted to adding nodes 14, 15.

In the error feedback, one may distinguish between the self-feedback and the external feedback. In the first case, the estimating error of a submodel (4) is supplied to the same submodel (4), and in the other case, the estimating error of a submodel (4) is supplied to

25   another submodel (5). At adding nodes 14, 15 an overall error is generated from the individual (weighted) estimating errors and is supplied to respective submodel 4, 5.

An external feedback is preferably implemented only if certain state variables Z or parameters P appear in parallel in several submodels. In this case, state variables Z and

30   parameters P may be adjusted with the other submodels.

For a state variable $Z_{1,j}$ in the jth submodel, which also occurs in submodels I = j+1, ..., j+n, the following difference equation is obtained:

$$Z_{1,j,k+1} = f(Z_{j,k}, P_{j,k}, I_{Batt,j,k}, T_{Batt,k}) + \sum_{i=j\ldots n} k_{z1,l,j} * (U_{Batt,i,k} -$$

$$U_{Batt,i,k^\wedge})$$

5   In this context, $f(Z_{j,k}^r \ P_{j,k} \ I_{Batt'j,k} \ T_{Batt,k})$ is the righthand side of a state difference equation for state variable $Z_{1,j}$ of the jth submodel having the input variables: filtered battery current $I_{Batt,j,k}$ and battery temperature $T_{Batt,k}$ as well as the parameter vector $P_{j,k}$ in the kth time step.

For a constant parameter $P_{1,j}$ in the jth submodel, which also occurs in submodels $i = j+1, \ldots,$
10   j+n, we obtain the following:

$$P_{1,j,k} + 1 = P_{1,j,k} + \sum_{i=j\ldots n} kP_{1,i,j} * (U_{Batt,l,k} - U_{Batt,l,k^\wedge})$$

The amplifications $k_{i,j}$ of weighting units 10-13 may be ascertained in a submodel 4, 5 in the
15   case of a Luneberg observer by pole specification, and if a Kalman filter is used for submodels 4, 5, by minimization of a quality criterion such as, for instance, the minimum estimating error variance.

If the current working range and/or frequency range is located outside the valid working
20   range and/or frequency range of a submodel 4, 5, there is not allowed to be an error feedback from such a submodel (e.g. submodel 5) to another submodel. In such a case, therefore, weighting factors $k_{i,j}$ of the corresponding weighting units (e.g. weighting unit 11) are set to zero. That means that $k_{i,j} = 0$ if the working range of the ith submodel is left.

25   In the system shown in Figure 3a, battery current IBdtt is supplied to state variable and parameter estimator 1. According to another specific embodiment according to Figure 3b, submodels 4, 6 may also be supplied with a (filtered) battery voltage U_{Batt} as input variable. Submodels 4, 5 would, in this case, estimate a battery current $U_{Batt^\wedge}$. The adjustment of the submodels is made via battery voltage $U_{Batt,1}, U_{Batt,2}, \ldots,$ via battery currents $I_{Batt,1}, I_{Batt,2}, \ldots,$
30   if the battery voltage ¹is specified as an input variable and the battery current is specified as an output variable of the submodels.

State variables and/or parameters which were estimated by a submodel (4) and are also included in another submodel (5) are preferably also supplied to the other submodel (5). Connecting lines 30, 31 are provided to do this. In the other submodel (5) the values may be used as a starting values, as a fixed value or as a correcting values for the estimation.

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Besides the state variables Z and the parameters P, submodels 4, 5 also supply the error variances (var_1, var_2, ...) of the variables. With that one may judge, for instance, whether the accuracy of the estimated variables Z, P is sufficient for the subsequent calculations of the loading state, the capacity and/or the load that is able to be drawn from the battery.

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In a further variant, the adjustment of the submodel takes place additionally via the battery voltages $U_{Batt,1}$, $U_{Batt,2}$, ..., i.e. the structure as in Figure 3a or 3b is used twice simultaneously, once using a submodel solved according to the battery voltage and once using a submodel solved according to the battery current. The simultaneously estimated state

15   variables and parameters from the individual submodels of the two structures may then be, for example, linked, weighted using their error variance, to an estimating variable, according to the already described way of linking variables that are estimated in parallel in various submodels.

20   For the optimum utilization of all submodels 4, 5, the operating variables of battery 3 should run through the entire working ranges and frequency ranges of submodels 4, 5 during the course of the calculation. If the electrical network, to which battery 3 is connected, supplies too little stimulation (e.g. load fluctuations), the quantities are not able to be estimated accurately enough. If the stimulations in the network are low, the internal resistance R_i of

25   battery 3 is able to be estimated only very inaccurately. In response to stimulation over a longer period, especially in the case of safety-critical applications, problems may arise since no accurate statement may be arrived at on the capacity of the battery.

State variable and parameter estimator 1 therefore includes a stimulator 16, which is in a

30   position to intervene actively in the electrical network and to set the working range and/or the frequency range of battery 3 or of the network in a desired manner. Stimulator 16 intervenes actively in the electrical network if the error variance of predefined state variables Z or parameters P is too large for a predefined time duration. The variances var calculated by the individual submodels 4, 5 are supplied to stimulator 16 as input variables.

The intervention in the electrical network by stimulator 16 takes place, for example, by specifying a new generator setpoint voltage UGen,soll (in the case of a vehicle generator), a load response time constant taUGen of a generator controller and/or by suitable users being switched on and off. By doing this, a battery current curve I_{Batt}, voltage curve U_{Batt} and or frequency curve, suitable for estimating the respective state variable Z or the respective parameter P may be impressed. Ideally, the desired battery current curve I_{Batt} (or a voltage curve U_{Batt}) is specified in such a way that it transfers battery 3 into a working range A and excites it in a frequency range f, in which one of the submodels (e.g. submodel 5) which includes the estimating variable, is particularly accurate, and consequently the estimated variable is able to be determined very accurately. Naturally, in this context, the distance of this new working range from current working range A of battery 3 and the maximum admissible amplitudes of control variables $U_{Gen,soll}$, tau_{Gen}, I_{Last} as well as the maximum permitted duration of the control intervention have to be taken into consideration.

The method of operating of stimulator 16 in Figure 1 is shown, for instance in Figure 4. The method begins at step 20 with the initializing of times t_P and t_{stim} to the values $t_P = 0$, $t_{stim} = 0$. In this context, t_P denotes a time in which a parameter P is being monitored, and t_{stim} denotes a stimulation time.

In step 22 it is checked whether the error variance var_P is greater than a maximum error variance $var_{P,max}$. If not (N), stimulator 16 remains deactivated. If, for a time duration t_P, error variance var_P remains greater than $t_{P,max}$ (step 23) and on the other hand greater than $var_{P,max}$, a current curve $I_{Batt,soll,P}$, that is assigned to parameter P, is impressed (step 24 and 26). This takes place until variance var_P of parameter P is less than or equal to maximum variance $var_{P,max}$ of this parameter P or the duration of stimulation tstim is greater than a predefined maximum duration $t_{stim,max}$ (checking in step 27) The variable t_{stim} for the duration of stimulation is increased iteratively in step 25 by respectively one scanning period T_{Ab}.

Figure 5 shows a special layout of a state variable and parameter estimator 1 for determining the ohmic internal resistance R_i of a lead battery 3. The internal resistance R_i of a lead battery 3 is a decisive quantity in the determination of the state of a battery, such as the capacity of battery 3 or the load that may still be drawn from it.

State variable and parameter estimator 1 includes two mathematical submodels 4, 5, of which the first has valid application over the entire frequency range, and second submodel 5 is only applicable at frequencies equal to or greater than 1 kHz. Accordingly, no filter is preconnected to first submodel 4, but a highpass filter 7 is preconnected to second submodel

5   5.

First submodel 4 includes a mathematical model description of the equivalent circuit diagram of Figure 2a. Second submodel 5, on the other hand, includes a mathematical description of the equivalent circuit diagram of Figure 2b, which is essentially only made up of internal

10   resistance R_i of battery 3. For, if we restrict ourselves to a frequency range of the order of magnitude of 1 kHz, and examine only high-frequency alternating components of current I_{Batt} and voltage U_{Batt}, the capacitors of the equivalent circuit diagram of Figure 2a may be regarded as being short-circuited. In this case, the only remaining component is the internal resistance R_i of the battery. In the following case, first submodel 4 is valid only for discharge

15   operation, since internal resistance R_i of battery 3, in loading operation, may be estimated only with difficulty from the few measured quantities current I_{Batt}, voltage U_{Batt} and temperature T_{Batt}.

For first submodel 4, to which the estimating errors $U_{Batt} - U_{Batt}^{\wedge}$ or $U_{Batts} - U_{Batts}^{\wedge}$ are

20   supplied, the following applies:
$R_{i,k+1} = R_{i,k} \, k_{11} \, (U_{Batt} - U_{Batt}^{\wedge}) + k_{21} \, (U_{Batt-} - U_{Batt-}^{\wedge})$
For second submodel 5
$R_{i,k+1} = R_{i,k}$

25   The value calculated from submodel 4 for internal resistance R_i of battery 3 is supplied to second submodel 5 and may there be used as the initial value, for example. In this case, the weighting units for second submodel 5, having weighting factors k22 and k12, may be omitted. On the other hand, weighting units 10, 11, for the error feedback into submodel 4, remain in force.

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It should be observed that, in loading operation, weighting factor 11 should be set to zero, since first submodel 4 is not valid for loading operation. Weighting factors k11 and k21 may be determined, for example, via an observer design according to Luenberg or Kalman.

LIST OF REFERENCE NUMERALS

1	state variable and parameter estimator
2	load predictor
3	battery
4	first submodel
5	second submodel
6-9	filter
10-13	weighting units
14,15	adding nodes
16	stimulator
17,18	adding nodes
20-27	method steps
30,31	connecting lines